Cultivar and nitrogen effects on yield and grain protein in irrigated Durum wheat

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Abstract

The grain yield and nitrogen use efficiency of durum wheat vary in response to genotypic and nitrogen fertilization were studied in field during two growth seasons. The aim of this study was to evaluate the effects the N fertilizer rate on grain yield and quality under irrigated desert conditions in relation to N utilization. Six durum wheat cultivars (Duraking, Havasu, Kronos, Ocotillo, Orita, Topper) were grown in field trails under irrigated regimes at five N levels (0, 65, 110, 160, 240 lbs/acre) in 2010-2011 and six N levels (0, 65, 110, 160, 240, 360 kg ha^{-1}) in 2011-2012 at Maricopa Ag Center. The results showed the varieties and N levels both significantly affected grain yield, grain protein concentration, and nitrogen use efficiency. A simple and rapid method to measure crop N status using SPAD meters was also developed. The results showed that using the differences in SPAD readings between the first and second fully expanded leaves is a useful way to improve effectiveness of SPAD meters in durum wheat N management.

Introduction

Nitrogen is the most important nutrient for durum wheat in irrigated dessert in Arizona. Large amount of N fertilizer is often applied for higher yield and better grain quality to obtain premium prices. Although N fertilizer input is high in durum wheat, growers in the region often find it difficult to apply an adequate amount of N at the right time to produce desirable grain yield and protein content. Many growers in Arizona use fixed N fertilizer programs to manage durum wheat crops. In these programs, N fertilizer can be under- or over-applied in the field due to different crop growth and N demand from year to year. When crop yield is high due to favorable growing conditions, N fertilizer applications from fixed programs are often not sufficient enough for the crop to attain the desirable 13% protein content. When crop yield is low, N fertilizer is often over-applied in fixed programs, resulting in protein contents higher than the desirable 13% without economic gains from N fertilizer application. In either case, growers' profitability is reduced.

Current recommendations for durum wheat N management are based on pre-plant soil sampling and in-season tissue testing (Ottman and Thompson, 2006). While many growers test their soils before planting, few conduct in-season tissue analysis for N management. This is due to the fact that the vast majority of N in durum wheat is split-applied at almost every irrigation event from 3-4 leaf stage to flowering in Arizona. Very often, growers are not able to receive laboratory test results before their next N application, discouraging them from using this powerful tool. Therefore, there is a need for simple and rapid methods that enable growers to estimate crop N status and make N application decisions based on these estimations in the field.

The ability to predict crop yield and/or grain protein content at anathesis has significant application in durum wheat in irrigated desert conditions. If crop yield and/or grain protein content can be predicted, the information can be used to guide growers on N management for desirable grain yield and grain protein. In this study, we tested the potential of SPAD meter, remote sensing, and crop modeling in prediction crop yield and/or grain protein.

Materials and Methods

Field experiments were conducted at the University of Arizona's Maricopa Agricultural Center at Maricopa, Arizona in 2010–2011 and 2011-2012 growing seasons. A split plot design with four replications was used with six durum wheat cultivars as main treatments. Durum wheat cultivars included Duraking, Topper, Kronos, Havasu, Orita, and Ocotillo. Five nitrogen rates were used in the 2010-2011 growing season: 0, 65, 110, 160, and 240 lbs/acre. An extra rate of 360 lbs/acre was included in the second growing season. Nitrogen fertilizer in the form of urea was hand-applied to each plot at different growth stages according to Table 1. The fertilizer was incorporated into the soil with irrigation water immediately after N application.

Sudangrass cover crops were grown in the summers before durum wheat planting to remove excess N from the soil and reduce variation in soil fertility. As a result, pre-plant soil samples showed that there was less than 3 ppm NO_3-N available for the durum wheat crop in the top 90 cm soil. Last cutting of sudangrass was conducted and fields prepared for durum wheat planting in early September of each growing season. To ensure P was not the limiting factor in the study, 50 lb/acre of phosphate in the form of 0-45-0 (N-P-K) fertilizer was applied before planting.

Durum wheat was planted into dry soils on flat ground on December 15 in 2010 and December 9 in 2011 and irrigated immediately after planting. The planting rate was 145 lb/acre with a row spacing of 7.5 inch and a planting depth of 1 inch. The experimental fields were flood irrigated to avoid water deficits.

Durum wheat plants were destructively sampled from the experimental plots on five dates in each growing season: January 18, February 24, March 22, April 7, and June 2 in 2011 and January 10, February 16, March 13, April 4, and May 24 in 2012. Plants in two 0.5 m row lengths within each plot were cut at the soil surface and immediately placed in coolers. Plant biomass was then oven-dried to obtain the dry weight of each sample under 65^{o}C with ventilation. The dried biomass was finely ground and samples were prepared for nitrogen content analysis. A Carlo Erba elemental analyzer was used to obtain the percent nitrogen content of each plant sample. The mature crop was harvested with a plot combine on June 2, 2011 and May 24, 2012. Crop yield was recorded and a sample of grain from each plot was analyzed for grain N content.

At jointing, flag leaf, and anthesis stage in both growing seasons, SPAD readings on the first and second fully expanded leaves was recorded with a chlorophyll meter SPAD 502 (Minolta Camera Co., Osaka, Japan). A total of 15 plants were measured in each plot and the mean values of the 15 plants were used for analysis.

Sufficiency index (SI) was calculated as the ratio of any SPAD readings with SPAD readings in the treatment with highest N rate in each year. In addition, differences between SPAD of second and first fully expanded leaves (SPAD21) were also calculated.

$$SI = \frac{SPAD1}{\text{SPAD1 in the treatment with highest N rate}} \qquad (2)$$

$$SPAD21 = SPAD2 - SPAD1 \qquad (3)$$

where SPAD1 and SPAD2 are SPAD readings of the first and second newly full expanding leaf, respectively.

From these data, the relationship of durum wheat biomass and plant N content in the highest N fertilizer rate treatment (N5) in the 2010-2011 growing season and two highest N fertilizer rate treatments (N5 and N6) in the 2011-2012 growing season was developed according to the dilution law. The following equation was fitted to shoot N concentration (%) and plant aboveground dry mass (DM, ton ha^{-1}) data:

$$Nc\ (\%) = a \times DM^{-b} \qquad (1)$$

where Nc is the critical shoot N concentration at which additional N uptake no longer increases plant growth, a and b are parameters.

Using the relationship of Nc and plant biomass, nitrogen nutrition index (NNI) was calculated for each plot by dividing actual N concentration by Nc. A value of NNI=1 indicates plants have optimal N status and a value of NNI < 1 indicates N deficiency in plants.

The following parameters were calculated according to Moll et al. (1982) and Fageria et al. (2008):

$$\text{Total N uptake } (N_t,\ \text{kg ha}^{-1}) = \text{Above ground dry matter} \times \%\text{N in dry matter} \qquad [1]$$

$$\text{Total grain N uptake } (N_g,\ \text{kg ha}^{-1}) = \text{Grain yield} \times \text{GNC} \qquad [2]$$

$$\text{N uptake efficiency (NUpE, kg } N_{plant}\ \text{kg } N_{fertilizer}^{-1}) = \frac{N_t}{F_x} \qquad [3]$$

$$\text{N utilization efficiency (NUtE, kg grain kg } N_{plant}^{-1}) = \frac{\text{Grain yield}}{N_t} \qquad [4]$$

$$\text{N use efficiency (NUE, kg grain kg N}_{\text{fertilizer}}^{-1}) = \text{NUpE} \times \text{NUtE} \quad [5]$$

$$\text{N harvest index (NHI, \%)} = \frac{N_g}{N_t} \times 100 \quad [6]$$

$$\text{N recovery efficiency (RE, \%)} = \frac{N_x - N_0}{F_x} \times 100 \quad [7]$$

$$\text{Agronomic efficiency (AE, kg grain kg N}_{\text{fertilizer}}^{-1}) = \frac{G_x - G_0}{F_x} \quad [8]$$

where N_t and N_g are total above ground plant N and N in durum wheat grain at maturity, N_0 and G_0 are N uptake and grain yield of unfertilized plot at maturity, and N_x and G_x are plant N uptake and grain yield under N fertilizer rate x (F_x).

Results and Discussion

Grain yield and GNC

There were no differences in grain yield among the six durum wheat cultivars in the 2010-2011 growing season (Table 2). In the 2011-2012 growing season, cultivars Duraking, Kornos, and Orita had higher grain yield compared to Topper and Ocotillo. Grain yield of Duraking was 25% greater than that of Ocotillo. While Ocotillo had the lowest grain yield, its GNC was generally higher among the six cultivars in both growing seasons (Table 3). Cultivar Duraking had the highest grain yield but lower GNC among the six cultivars in the 2011-2012 growing season. The results indicate that there were significant variations in grain yield between growing seasons and that GNC varied with growing seasons and N fertilizer rates.

Averaged across varieties, both grain yield and GNC increased as N fertilizer rate increased (Fig. 1B and 1C). Durum wheat grain yield increased from 1.75 Mg ha^{-1} in the unfertilized treatment to 8.11 Mg ha^{-1} at 403 kg ha^{-1} N fertilizer rate, while GNC increase from 16.5 to 24.5 g kg^{-1}. Grain yield and GNC at 403 kg ha^{-1} N fertilizer rate treatment were 460% and 50% higher compared to the unfertilized treatments. The GNC was significantly higher in the 2010-2011 growing season compared to the 2011-2012 growing season. The difference is probably due to warmer February and March in the 2010-2011 growing season (AZMET, 2013). Both grain yield and GNC had quadratic relationship with N fertilizer rates, with maximal grain yield and GNC occurring at 403 kg ha^{-1} and 341 kg ha^{-1} N fertilizer rates, respectively.

Nitrogen uptake efficiency and NUtE

There were no differences in NUpE among durum wheat cultivars in the 2010-2011 growing season (Table 2). In the 2011-2012 growing season, cultivar Duraking and Havasu had higher NUpE compared to other four cultivars. Although there was cultivar × N fertilizer interaction in NUtE, cultivar Duraking generally had the highest NUtE and cultivar Ocotillo had the lowest NUtE in both growing seasons (Table 3). The differences in NUE were not significant in the 2010-2011 growing season, while Duraking and Ocotillo had the highest and lowest NUE, respectively, in the 2011-2012 growing season, indicating that durum wheat cultivars yielded differently for each unit of N fertilizer applied to the crop.

The relationship of NUpE of durum wheat cultivars and N fertilizer rate was described by a power function (Fig. 1). Nitrogen uptake efficiency of durum wheat cultivars varied significantly with N fertilizer rate, ranging from 1.52 kg N_{plant} kg $N_{fertilizer}^{-1}$ at the 73 kg ha^{-1} N fertilizer rate to 0.91 kg N_{plant} kg $N_{fertilizer}^{-1}$ at the 403 kg ha^{-1} N fertilizer rate. Nitrogen utilization efficiency decreased linearly as N fertilizer rate increased, from 35.7 kg grain kg N_{plant}^{-1} in the unfertilized treatment to 24.5 kg grain kg N_{plant}^{-1} at the 403 kg ha^{-1} N fertilizer rate. Decreases in both NUpE and NUtE with increased N fertilizer rate resulted in a negative correlation between NUE and N fertilizer rate. Nitrogen use efficiency decreased from 51.4 kg grain kg $N_{fertilizer}^{-1}$ at the 73 kg ha^{-1} N fertilizer rate to 23.9 kg grain kg $N_{fertilizer}^{-1}$ at the 403 kg ha^{-1} N fertilizer rate, with a faster rate of decrease at the lower range of N fertilizer rate.

Compared to NUtE, NUpE had an overall higher correlation with NUE ($r = 0.82$ for NUtE and NUE vs. $r=0.94$ for NUpE and NUE). When N fertilizer rate was lower than 123 kg ha^{-1}, the differences between the correlation coefficients were more significant ($r = 0.36$ for NUtE and NUE vs. $r=0.88$ for NUpE and NUE), indicating NUpE was more influential on NUE under low N supply. The correlation coefficients were 0.66 for NUtE and NUE and 0.85 for NUpE and NUE when N fertilizer rate was 185 kg ha^{-1} or higher.

SPAD readings affected by leaf age and positions along leaf blade

In the 2010-2011 growing season, SPAD meter readings were taken from leaves with different ages and from different positions along the leaf blade for the Duraking cultivar. Because durum wheat leaves emerge and unfurl over a substantial period of time, the leaf blade age varies considerably from the base to the tip. Thus SPAD readings taken from different positions along the leaf blade varied significantly. SPAD readings along the leaf blade were lower at positions closest to the ligule or leaf base, increased with distance away from the leaf base, and reach the maximum at 60-70% from leaf base (Table 4). Readings on leaves from category 1 (the most recent fully expanded leaf preceding an emerging folded leaf) were highest when taken at 67-76% of the total leaf length from leaf base, 60 to 65% for leaves in category 2 (the most recent fully expanded leaf preceding an emerged and half-way unfurled new leaf), and 56 to 61% for leaves in category 3 (the second most recent fully expanded leaf preceding a recently expanded leaf and an emerging folded leaf). This indicates that both leaf age and position along leaf blade affect SPAD meter readings in the field.

The SPAD readings generally increased with leaf age (Table 4). The SPAD reading differences between the leaves in category 2 and category 1 were 1.2, -0.3, 1.1, 3.4, and 2.0 SPAD units for the N rate of 0, 73, 123, 185, and 269 kg ha^{-1}, respectively. This indicates that leaf age is an important factor that needs to be considered when collecting SPAD measurements. The differences between the category 3 and category 1 readings were 0, 0.1, 4.2, 5.8, and 5.0 SPAD units for the N rate of 0, 73, 123, 185, and 269 kg ha^{-1}, respectively, indicating that plants from the higher N rate can keep leaves in the lower position greener relative to the first fully expanded leaves. This also indicates that it is possible to correlate the differences between the leaves from different positions with crop N status.

Relationships between various SPAD indices and NNI

The SPAD readings had a linear relationship with log transformed values of NNI (Figure 3). The regression line of SPAD meter readings from the first fully expanded leaf and ln(NNI) had a R^2 of 0.36. The SI explained significantly higher variation in ln(NNI) with an R^2 of 0.57, indicating that the use of a high N reference can significantly improve the effectiveness of SPAD readings to guide N applications. When SPAD readings from the second leaf were used as reference, the regression equations of NDSPAD and SPAD21 with ln(NNI) explained 53% and 57% of variation in ln(NNI), respectively. This indicates that using the second leaf as a reference could also improve the effectiveness of SPAD meter readings without requiring high N reference strips in the field. Since a NNI value of 1 [when ln(NNI)=0] indicates the readings at which there is sufficient N in durum wheat plants, our studies suggests that durum wheat crops reach sufficient N status when values of SPAD1, SI, NDSPAD, and SPAD21 are over 48.90, 0.98, 0.028, and 2.75, respectively.

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Table 1. N application rate at different growth stage

Growth stage	Date		Nitrogen rate (lb N/acre)					
	2010-2011	2011-2012	N1	N2	N3	N4	N5	N6*
Pre-plant	N/A	12/8/2011	0	0	0	0	0	80
2-4leaf	1/18/2011	1/11/2012	0	15	30	55	80	100
Jointing	3/9/2011	2/28/2012	0	10	20	30	40	50
Flag leaf	3/24/2011	3/13/2012	0	20	30	40	60	60
Anthesis	4/11/2011	4/9/2012	0	20	30	40	60	70
Total			**0**	**65**	**110**	**165**	**240**	**360**

* The rate was only included in the 2011-2012 growing season.

Table 2. Effects of durum wheat cultivar on grain yield, grain N, total plant N, N recovery efficiency (RE), agronomic efficiency (AE), N uptake efficiency (NUpE), and N use efficiency (NUE). †

Year	Cultivar	Grain yield (Mg ha^{-1})	Grain N (kg ha^{-1})	Total N (kg ha^{-1})	RE (%)	AE (kg grain kg $N_{fertilizer}^{-1}$)	NUpE (kg N_{plant} kg $N_{fertilizer}^{-1}$)	NUE (kg grain kg $N_{fertilizer}^{-1}$)
2010-2011	Ocotillo	4.32	102.5 ab*	150.3 a	80.2	21.2 d	1.30	36.3
	Orita	4.50	103.5 a	152.2 a	89.3	25.5 ab	1.32	38.8
	Kronos	4.31	96.4 ab	136.7 bc	83.4	26.2 a	1.23	37.9
	Havasu	4.53	104.3 a	153.5 a	85.6	23.8 bc	1.31	38.6
	Duraking	4.30	94.7 b	135.3 c	81.7	26.8 a	1.19	36.5
	Topper	4.44	101.7 ab	148.1 ab	83.1	23.1 cd	1.30	38.0
	Cultivar	0.63†	0.04	<0.01	0.57	<0.01	0.14	0.63
	Cultivar × Nrate	0.43	0.40	0.23	0.67	0.14	0.79	0.88
2010-2011	Ocotillo	4.80 d	106.1 c	163.1 d	78.7 b	24.1 bc	1.12 b	33.0 c
	Orita	5.74 ab	120.1 a	174.5 bc	76.8 b	24.0 c	1.14 b	36.9 b
	Kronos	5.80 ab	119.4 ab	169.9 bcd	77.2 b	24.1 bc	1.14 b	37.6 b
	Havasu	5.51 bc	124.9 a	186.1 a	87.1 a	22.6 c	1.25 a	36.1 b
	Duraking	5.99 a	124.3 a	178.8 ab	87.6 a	26.0 ab	1.25 a	39.8 a
	Topper	5.30 c	112.4 bc	166.9 cd	84.4 ab	26.5 a	1.16 b	35.8 b
	Cultivar	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01
	Cultivar × Nrate	0.10	0.07	0.23	0.18	0.06	0.38	0.21

* Within columns in each growing season, means followed by the same letter are not significantly different according to LSD (0.05).

† P values for cultivar effects and cultivar × N fertilizer rate effects.

Table 3. Effects of durum wheat cultivar and N fertilizer rate on grain N concentration (GNC), N harvest index (NHI), and N utilization efficiency (NUtE)[†].

Year	Cultivar	GNC (g kg^{-1})						NHI (%)						NUtE (kg grain kg N_{plant}^{-1})					
		0[‡]	73	123	185	269	403	0	73	123	185	269	403	0	73	123	185	269	403
2010-2011	Ocotillo	18.0	23.0 a*	23.3	26.5 a	26.8	--	68.4	68.9	69.4	68.6	67.1 ab	--	39.1	30.1 b	29.9	26.1 c	25.0 c	--
	Orita	17.5	20.8 c	23.0	25.3 ab	26.8	--	60.9	67.1	68.9	71.8	65.9 b	--	35.7	32.2 ab	30.4	28.6 b	25.0 c	--
	Kronos	16.0	21.5 bc	22.0	25.3 ab	25.8	--	64.0	70.9	70.8	71.2	70.2 a	--	40.7	33.0 a	32.5	28.6 b	27.5 ab	--
	Havasu	15.8	20.5 c	23.5	24.5 bc	27.5	--	66.5	70.4	71.0	67.3	65.8 b	--	42.1	33.9 a	30.4	27.5 bc	23.9 c	--
	Duraking	17.0	22.3 ab	22.3	23.0 c	25.0	--	63.0	69.6	68.7	70.7	70.7 a	--	36.7	31.7 ab	30.8	30.9 a	28.7 a	--
	Topper	17.3	22.3 ab	23.3	24.5 bc	25.8	--	67.3	70.0	71.6	68.5	66.9 ab	--	39.2	31.5 ab	30.8	27.9 bc	25.9 bc	--
2011-2012	Ocotillo	23.3 a	20.5	21.8 a	22.5 ab	25.8 ab	26.3 ab	54.6 bc	66.6	74.1	66.8 b	66.2	60.6 b	24.3 b	32.9 bc	34.2	29.6 c	26.0 b	23.1 c
	Orita	17.0 b	19.5	19.5 b	21.3 bc	24.0 cd	25.8 b	63.0 ab	68.1	69.7	71.4 a	70.3	67.0 a	37.3 a	35.1 abc	35.7	34.0 abc	29.0 ab	26.2 ab
	Kronos	17.8 b	20.3	20.5 ab	20.5 c	23.3 d	25.3 bc	71.4 a	71.3	72.2	71.6 a	70.8	68.0 a	40.7 a	35.7 ab	35.2	35.2 a	30.5 a	27.3 a
	Havasu	16.8 b	21.5	22.0 a	23.8 a	26.5 a	27.3 a	67.2 a	67.3	66.3	67.1 b	69.5	65.3 ab	40.0 a	31.2 c	30.5	28.6 c	26.3 b	24.2 bc
	Duraking	17.0 b	19.0	19.5 b	22.0 bc	23.8 cd	25.3 bc	69.0 a	71.5	71.1	70.3 ab	71.3	66.9 a	40.9 a	37.9 a	36.5	32.1 abc	29.8 a	26.6 ab
	Topper	18.3 b	21.0	19.5 b	22.5 ab	24.8 bc	24.3 c	48.2 c	68.1	69.1	68.7 ab	68.3	66.9 a	26.3 b	32.1 bc	35.4	30.5 bc	28.0 ab	27.4 a

[*] Within columns in each growing season, means followed by the same letter are not significantly different according to LSD (0.05).

[†] Interactions of cultivar × N fertilizer rate were significant for the three variables.

[‡] The values in the row are N fertilizer rate treatments.

Table 4. SPAD readings affected by leaf age and position along leaf blade.

N rate (kg ha^{-1})	Leaf age category 1[†]		Leaf age category 2		Leaf age category 3	
	Position along leaf blade with highest SPAD reading (%)[‡]	Highest SPAD reading on leaf blade	Position along leaf blade with highest SPAD reading (%)	Highest SPAD reading on leaf blade	Position along leaf blade with highest SPAD reading (%)	Highest SPAD reading on leaf blade
0	71.2	39.1	64.2	40.3	56.3	39.1
73	70.2	42.9	60.4	42.6	59.8	43.0
123	75.9	47.7	63.7	48.8	61.3	51.9
185	67.5	51.3	63.1	54.7	59.3	57.1
269	67.1	52.5	64.7	54.5	60.9	57.5
Mean	70.4		63.2		59.5	

[†] Leaf age category 1 includes the most recent fully expanded leaf preceding an emerging folded leaf; leaf age category 2 includes the most recent fully expanded leaf preceding an emerged and half-way unfurled new leaf; leaf age category 3 includes the second most recent fully expanded leaf preceding a recently expanded leaf and an emerging folded leaf.

[‡] On each selected leaf, blade was divided into 15 sections with equal length starting from the leaf base to the apex. Leaf base was treated as 0% and leaf tip as 100%.

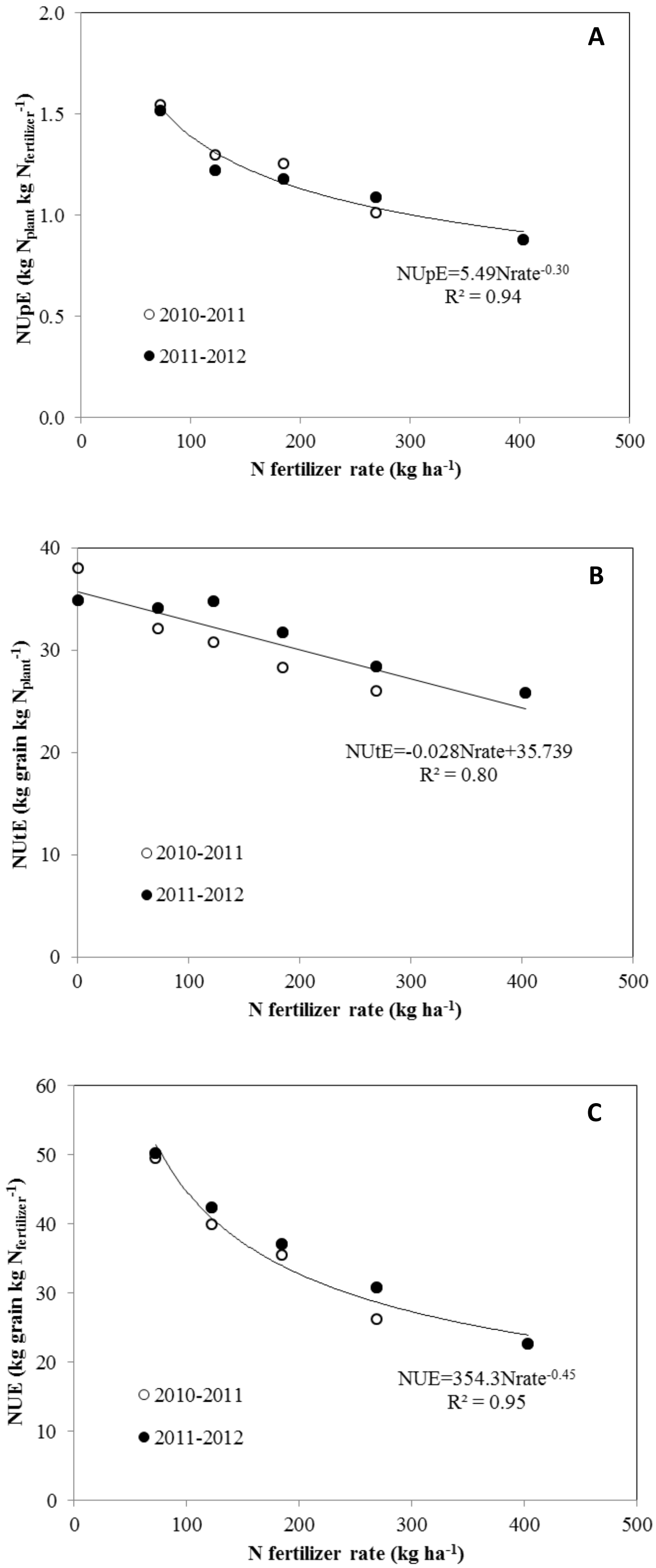
A
NUpE (kg Nplant kg Nfertilizer-1)
N fertilizer rate (kg ha-1)
NUpE=5.49Nrate-0.30
R² = 0.94
2010-2011
2011-2012
B
NUtE (kg grain kg Nplant-1)
NUtE=-0.028Nrate+35.739
R² = 0.80
C
NUE (kg grain kg Nfertilizer-1)
NUE=354.3Nrate-0.45
R² = 0.95

Fig. 1. Nitrogen uptake efficiency (NUpE), N utilization efficiency (NUtE), and N use efficiency (NUE) of durum wheat affected by N fertilizer rate.

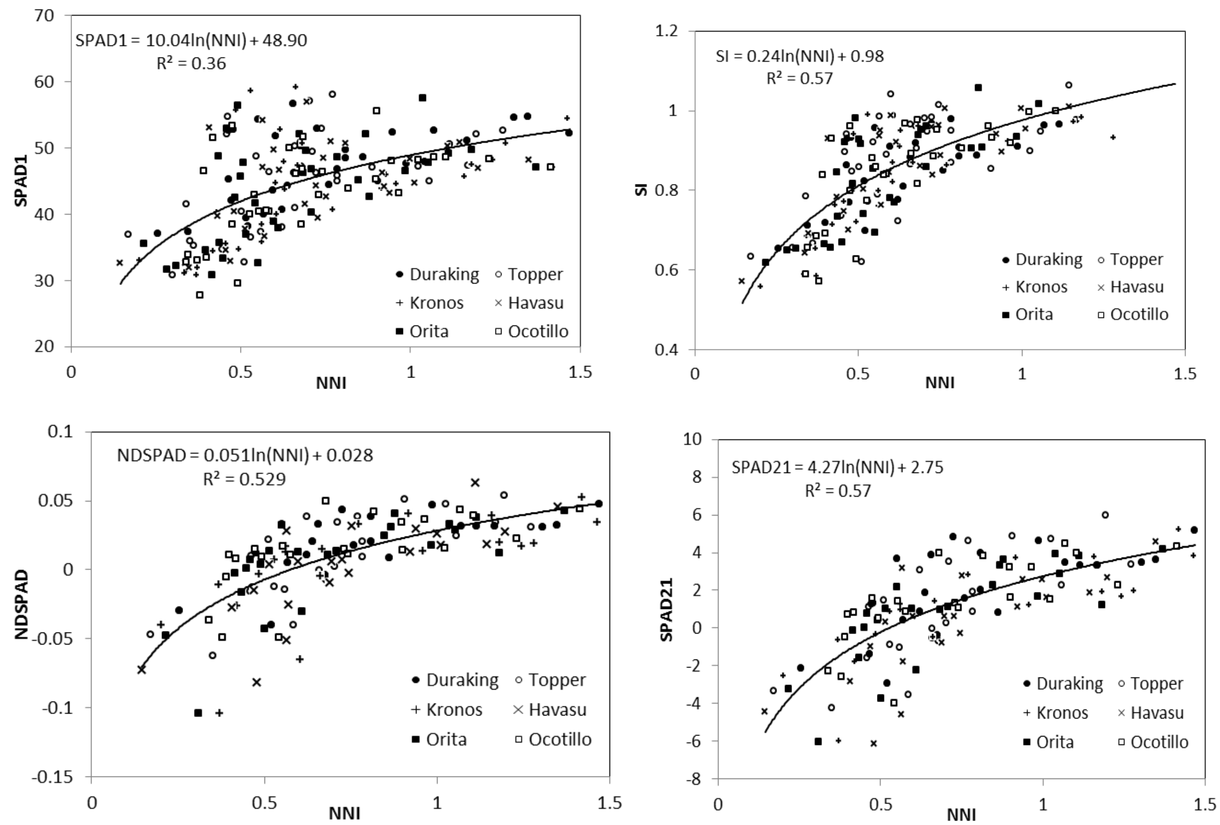

Figure 3. Relationship of SPAD indices and NNI. SPAD1: SPAD readings on the most recent fully expanded leaves; SI: Sufficiency Index or normalized SPAD index; NDSPAD: Normalized difference SPAD index; SPAD21: differences in SPAD readings between the second most recent and most recent fully expanded leaves.